CHAPTER 2

TECHNOLOGY DESCRIPTION AND UNDERLYING PHYSICAL PROCESS

2-1. Introduction. This section provides an overview of air sparging, describes various applications of the technology, and discusses the underlying physical processes that occur during IAS.

2-2. Overview of Air Sparging.

    a. Air sparging is the process of injecting air into the saturated subsurface to treat contaminated soil and groundwater. Air sparging mechanisms include partitioning of volatile contaminants from the aqueous phase to the vapor phase (stripping), for their subsequent transfer to and removal from the unsaturated zone; and, transfer of oxygen from the injected air to the aqueous phase to enhance aerobic microbial degradation of contaminants in the saturated zone, termed biosparging. Air sparging may be used to:

    (1) Treat saturated zone contamination in a source area (although its effectiveness in remediating non-aqueous phase liquids (NAPL) is as yet a matter of considerable debate, especially with respect to dense NAPL (DNAPL);

    (2) Treat dissolved phase contamination in a plume;

    (3) Contain a dissolved-phase plume; and/or

    (4) Immobilize contaminants through chemical changes.

These diverse applications are addressed, in turn, in the following four paragraphs.

    b. Treat Saturated Zone in a Source Area.

    (1) Saturated zone contamination exists at many locations where fuel hydrocarbons or organic solvents have been released into the subsurface. Such "source" areas contain contaminants dissolved in the aqueous phase, and also typically contain NAPL. Groundwater pump-and-treat, which until recently was often relied upon to treat such saturated zone contaminants, is a very slow remediation process and has been judged as having met with little success except as a containment tool (NRC 1994). With the dawning of this recognition, attention turned to alternative technologies. Although air-based remediation technologies such as SVE and BV gained favor for treatment of unsaturated zone contamination, they do not apply to the saturated zone. IAS, however, is an air-based technology that is meant to be applied within the saturated zone. The view was widely expressed by early practitioners that IAS can achieve site closure — implying treatment of both dissolved-phase and non-aqueous phase contaminants if present — much more rapidly than pump-and-treat

(Brown and Fraxedas 1991; Marley 1992; Angell 1992). As more experience was gleaned from applying IAS at numerous sites, these and other practitioners have tended to adopt a somewhat more circumspect view, especially with respect to its effectiveness in treating NAPL in the saturated zone and the capillary fringe.

(2) A secondary effect of applying IAS in a source area is that the resulting reduction in hydraulic conductivity in the source area reduces the rate at which groundwater flows through that area, thereby reducing the rate at which contaminants migrate from the source area, which in turn reduces the rate at which a downgradient plume is supplied with contaminants.

c. Treat Dissolved Phase in a Plume Area. Another common application of IAS is for the treatment of dissolved phase contamination in a plume, downgradient of source areas. Configurations used for aqueous-phase treatment include the installation of an array of air sparging points, spaced so that each individual ZOI overlaps. When the source is a release of light non-aqueous phase liquid (LNAPL) (e.g., gasoline, fuel oil), the dissolved plume is often primarily situated near the water table surface of an unconfined aquifer. In such cases IAS points can be conveniently located just below the plume to obtain the desired coverage. In a survey of 32 IAS case studies, Bass and Brown (1996) concluded that performance of IAS systems was generally better in systems treating dissolved-phase plumes than in systems treating adsorbed contaminants.

d. Contain a Dissolved Phase Plume.

(1) A third type of application of IAS is to effect containment of a dissolved-phase plume. A series of sparge points with overlapping zones of influence can be arrayed along a line perpendicular to the plume axis and within or just downgradient of the leading edge of the plume, so as to intercept it (e.g., Wade 1996; Payne et al. 1996). This approach can also be incorporated within a funnel-and-gate configuration (Pankow et al. 1993), in a manner similar to the placement of a permeable barrier or reactive wall, although use of impermeable funneling barriers such as sheet walls are not necessarily required with sparge curtains. The objective of this approach is to halt contaminant migration.

(2) Care must be taken to prevent diversion of a groundwater plume around a sparge curtain or sparge gate. Such a diversion can occur with implementation of IAS if air saturation values increase within the sparge zone, causing marked reductions in hydraulic conductivity there. This problem can be avoided by cycling or pulsing the IAS system, as is discussed in greater detail in paragraph 6-6b. With sparging trenches, the use of high permeability material can offset to some degree the loss of hydraulic conductivity due to air saturation.

(3) See Design Guidance for Application of Permeable Barriers to emediate Dissolved Chlorinated Solvents for information on funnel-and-gate systems or contact the USEPA Remediation Technologies Development Forum (RTDF) Permeable Barriers Working Group through USEPA's Technology Innovation Office, 401 M Street, S.W., Washington, D.C. 20460.

e. Immobilize Contaminants through Chemical Changes. A fourth way to potentially use IAS is to immobilize contaminants through chemical changes (e.g., oxidation of arsenic, its subsequent complexation with iron hydroxides, and precipitation). Aeration effects an increase in dissolved oxygen concentration in the groundwater, and an accompanying increase in oxidation-reduction potential (redox). Consequently, redox reactions can occur at or near IAS wells. While iron fouling of the IAS well screen would represent an adverse result, which would need to be avoided, immobilization within the aquifer of unwanted inorganic compounds such as heavy metals is a beneficial although potentially reversible effect (Marley and Hall 1996).

2-3. Air Sparging Technology Options. Air sparging can be performed by any of the following techniques:

a. Injection into the Saturated Zone. Injecting air directly into the saturated zone, termed in-situ air sparging, shall be emphasized in this EM. SVE often accompanies IAS for the purpose of controlling fugitive emissions of the VOCs that are carried to the unsaturated zone by IAS.

b. Vertical or Horizontal Wells. IAS has been performed using horizontal sparging and venting wells at numerous sites including at the USDOE Savannah River Site demonstration (Lombard et al. 1994). At the Hastings East Industrial Park, Hastings, NE, USACE Kansas City District employed a horizontal sparging well to intercept a dissolved plume downgradient of a source area, as well as a vertical sparging well within the source area itself (Siegwald et al. 1996). Horizontal and vertical wells can also be mixed within a single sparge and vent well field to afford greater control on injection or extraction rates at various locations, and to optimize costs.

c. Injecting Gases Other than Air. Injecting gases other than air (e.g., pure oxygen, ozone, methane, pure nitrogen, or nitrous oxide) may enhance the speed at which bioremediation proceeds or alter the conditions under which it occurs. The USDOE Savannah River Site demonstration (Lombard et al. 1994; Hazen et al. 1994) successfully incorporated injection of gaseous nutrients to stimulate aerobic methanotrophic cometabolic biodegradation of trichloroethylene (TCE). Methane was injected to serve as a source of carbon (injected continuously at a level of 1% methane in air, or intermittently at 4% methane in air), along with nitrous oxide (0.07%) and triethyl phosphate (0.007%) to serve as gaseous sources of nitrogen and phosphorus, respectively. Over the period of the multiyear demonstration, the majority of the estimated

contaminant mass was removed. An additional discussion of these techniques is provided in paragraph 5-7c.

2-4. Related Technologies.

    a. IAS is related to several other recognized remediation technologies, either as earlier versions or complimentary techniques:

    (1) The aeration of a well bore or tank is similar to air stripping for removal of VOCs from water, except that the stripping process is conducted within the well or container instead of in a packaged tower or tray tower.

    (2) The introduction of oxygen to the region below the water table is directly related to in-situ bioremediation. IAS can be an alternative to other means of introducing oxygen into the saturated zone.

    (3) The use of air for conveyance of VOCs is related to the process of SVE, which is often used in the vadose zone above IAS to recover the stripped VOCs.

    b. In-well aeration is a method that introduces air into the lower portion of a submerged well pipe, so that air bubbles rise within the pipe, with associated vapor-to-liquid and liquid-to-vapor mass transfer. This groundwater circulation well (GCW) technology has been termed in-well aeration (Hinchee 1994) and is related to airlift pumping. In its most common configurations, placement of two screens, one at the bottom of the pipe and a second at the water table surface, enables aquifer water to be drawn into the pipe at its lower end and aerated and stripped water to exit at or above the ambient water table (Figure 2-1). Depending on the degree of anisotropy (i.e., provided the anistropy is not too great), this circulation may create a widespread toroidal convection cell within the aquifer (Herrling et al. 1991). As with IAS, SVE is often employed to extract and treat the vapors brought upward within the well pipe. All of the factors that limit the effectiveness of pump-and-treat also limit the effectiveness of GCW technology. Paragraph 8-3 provides several potential configurations of in-well aeration. Otherwise this EM focuses on IAS, rather than GCW, technology.

    c. Pneumatic fracturing, a technique of injecting a high-pressure gas or liquid into the subsurface to enhance airflow in tighter formations (e.g., silt and clay), may not be beneficial to IAS unless fractures can be controlled so as to be closely spaced. Otherwise, diffusion-limited mass transfer in low-permeability strata will limit IAS effectiveness.

    d. Other enhancements to IAS have also been introduced. This EM attempts to encompass a broad view of IAS's potential capabilities and its limitations, as currently understood.
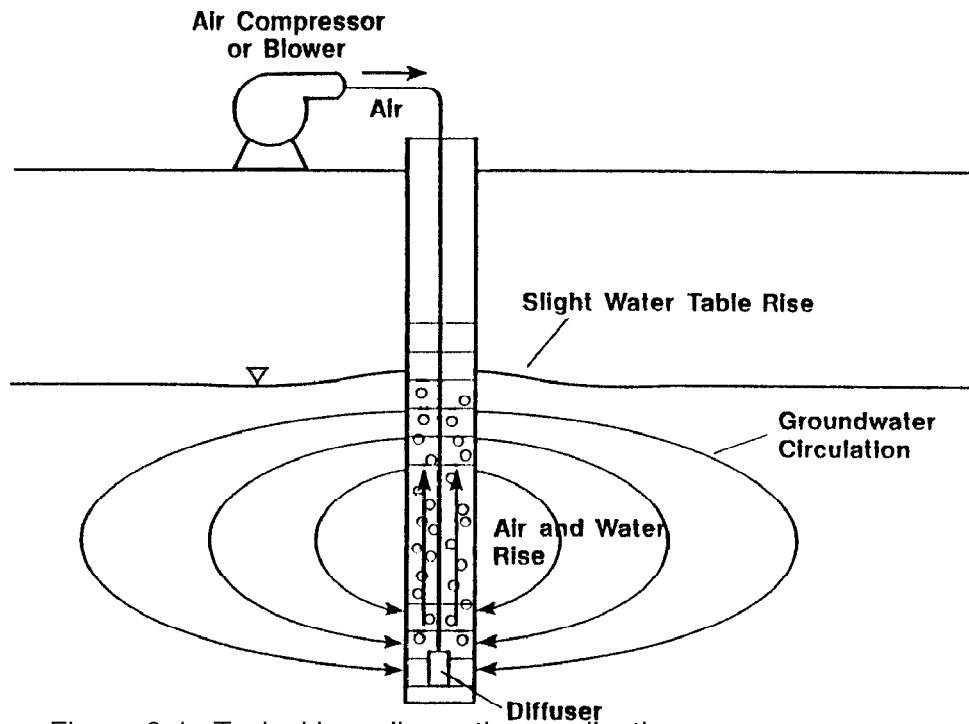
Figure 2-1. Typical in-well aeration application.
(after Hinchee 1994. Reprinted with permission
from *Air Sparging for Site Remediation.*
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Boca Raton, Florida. ©1994.)

2-5. Summary of Physical Processes.

        a. Detailed descriptions of the pneumatics and hydraulics of IAS have
been presented by several authors (e.g., Johnson et al. 1993; Ahlfeld et al.
1994); a somewhat abbreviated discussion will be offered here. Until about
five years ago, it was commonly assumed that IAS produces small air bubbles
that rise within the aquifer, which we may think of as "the aquarium model".
Illustrations of the aquarium model frequently showed a conical distribution
of air bubbles originating at the sparge point and moving upward and outward
to the water table (Brown and Fraxedas 1991; Angell 1992). It has since been
demonstrated in bench-scale research that bubble flow can occur, but only in
porous media having large (> 2mm diameter) interconnected pores, such as in
deposits consisting entirely of gravels (Ji et al. 1993; Brooks et al. 1996).
In soils, saturated-zone airflow resulting from air injection occurs in
discrete pore-scale or larger-scale channels, rather than as uniform bubbles
(Johnson et al. 1993; Ji et al. 1993). Figure 2-2 depicts channel flow at
the pore scale, and Figure 2-3 illustrates larger-scale channels, for the
cases of (a) IAS in homogeneous sand and, (b) IAS in heterogeneous sand. This
contemporary view of IAS sees it as a type of multiphase flow, in which a
continuous gaseous phase under pressure displaces the liquid phase from
certain pores or categories of pores within the aquifer formation. The
larger-scale channels represent a longitudinal extension of the pore-scale
displacement process, and are most apparent when airflow occurs predominantly
within preferred pathways. In the case of IAS in uniform, unstructured silt
or fine sand, large-scale channels will not be evident, although air
displacement at the pore-scale still takes the form of capillary fingering
(Clayton 1996). In the more common case of IAS in non-uniform soil, large-
scale channels are expected to predominate.

        b. Both soil stratigraphy and heterogeneity have a profound influence
on air channel location and density. For example, laterally continuous, low
permeability layers may induce air pocket formation beneath confining layers
(Figure 2-3). Soil layers characterized by low hydraulic conductivities, even
if thin, can have very high entry pressure requirements and may permit very
little upward movement of air through the aquifer.

2-6. Components of Injection Pressure. Whatever the geometry of the
displacement, the injection pressure measured at the well head required to
accomplish it has several components, as will be presented in the following
paragraphs. Note that the friction loss between well head and screen is only
part of the injection pressure requirements - there is also the loss in the
piping to the well and all the fittings. The following paragraphs emphasize
the loss between the well head and the screen because that is the portion that
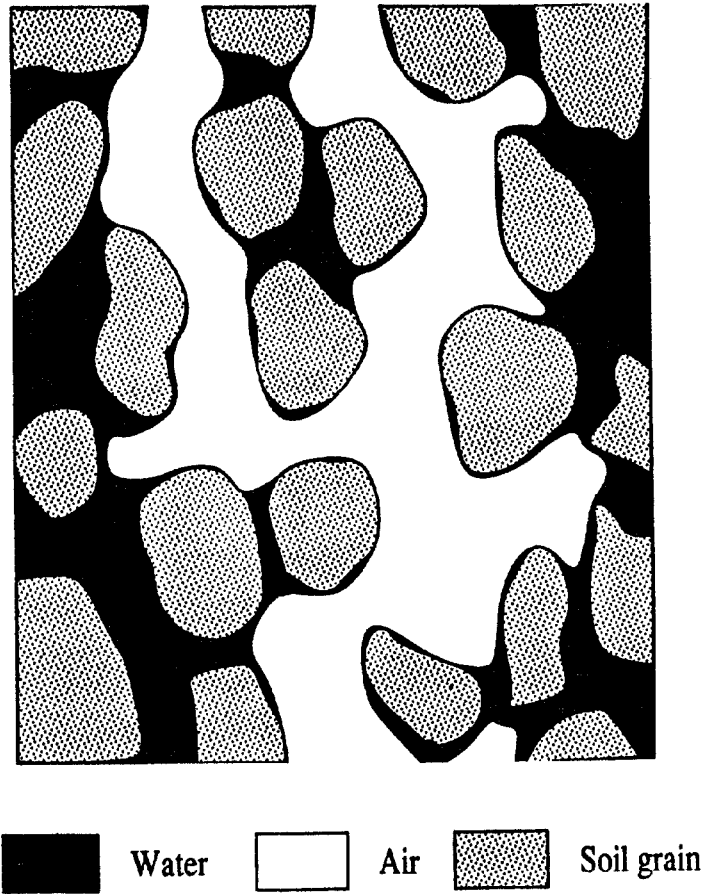affects the injection pressure that can be measured at the well head.

Figure 2-2. Schematic of channel flow at the pore scale showing interfaces between air and water.

(Ahlfeld et al. 1994. Reprinted by permission of Ground Water Monitoring & Remediation. Copyright 1994. All rights reserved.)
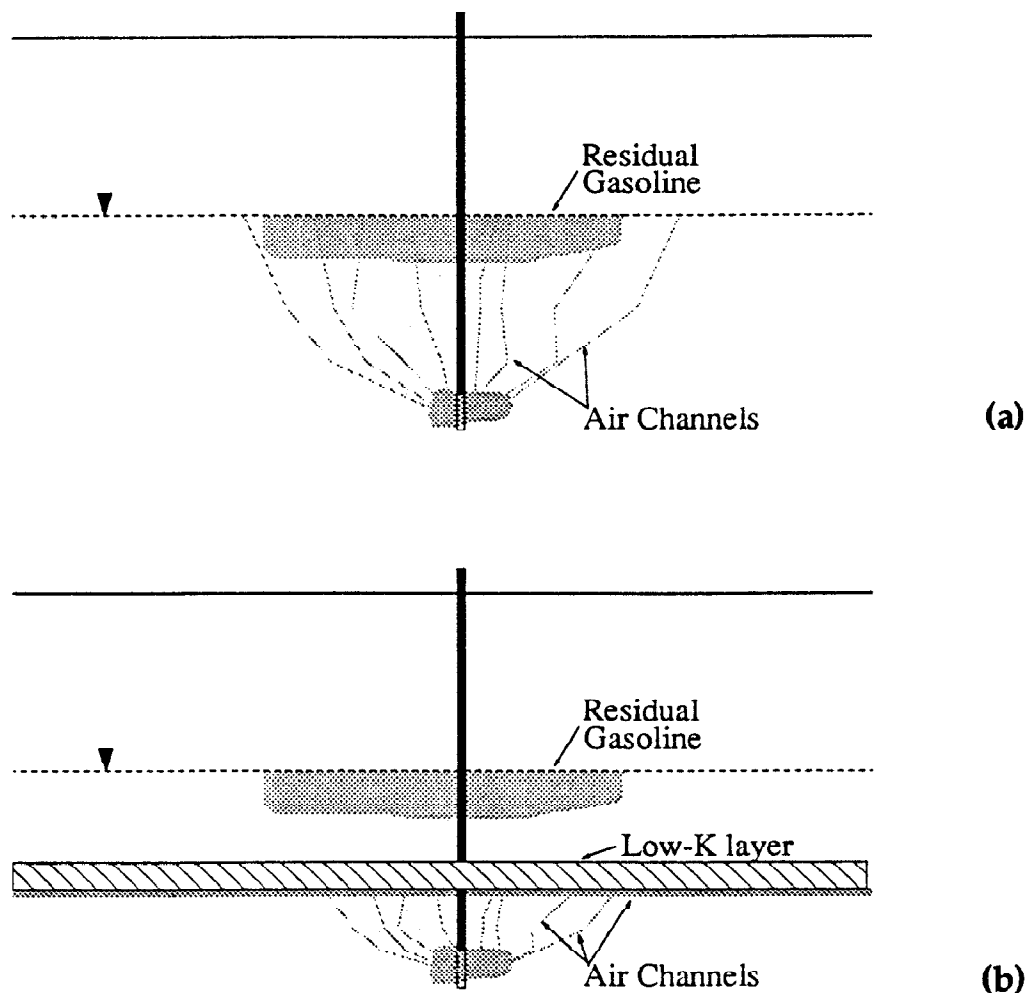
Figure 2-3. (a) Schematic drawing of airflow during in situ air sparging in homogeneous sand. (b) Schematic drawing of airflow during in situ air sparging in heterogeneous sand.
(Johnson 1994. Reprinted by permission from *Air Sparging for Site Remediation* Copyright Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida. ©1994.)

a. Hydrostatic Pressure. A key component of the injection pressure is the hydrostatic pressure needed to displace the column of water standing in the well pipe,

$$P_h = \rho_w \, g \, (z_s - z_w) \qquad\qquad [2\text{-}1]$$

where P_h is hydrostatic pressure (gm cm^{-1} sec^{-2}),
             ρ_w is the density (gm cm^{-3}) of the water,
             g is gravitational acceleration (cm sec^{-2}),
             z_w is the pre-sparging depth (cm) to the free-water surface within the sparge well,
             and
             z_s is the depth (cm) to the top of the IAS well screen.

Considering that 1.01×10^6 gm cm^{-1} sec^{-2} = 101 kPa = 14.7 psi, and that at typical values of water temperature and density, 14.7 psi = 33.8 ft. H$_2$O, it is useful to note that a hydrostatic pressure of 0.43 psi is required per foot of water column, i.e.,

$$P_h = 0.43 \, (z_s - z_w) \qquad\qquad [2\text{-}2]$$

for P_h expressed in psig and z_w and z_s in feet. Table 2-1 presents conversions among various other units of pressure and pressure head.

b. Frictional Losses in Pipe. The second component of the injection pressure is the headloss due to friction of fluid moving between the well head and the IAS well screen. Figure 5-6 of EM 1110-1-4001 is a friction loss chart (nomograph) for straight pipe for inlet air at 294° K and 101-kPa absolute pressure. Although the magnitude of friction loss can be significant, it may be neglected for typical applications of IAS such as ones that combine the following conditions: sparge well diameter $\geq$ 5 cm (2 inches), well pipe length $\leq$ 30 m (100 ft.), and airflow rate $\leq$ 0.4 m^3/min (15 cfm). For smaller sparge well diameters, longer well pipe lengths, and/or higher airflow rates, frictional losses will be more significant. Similar losses may also occur in aboveground piping and should be anticipated.

c. Filter Pack Air-Entry Pressure. The third component of the injection pressure is the air-entry pressure of the filter pack, if present between the well screen and the formation. This value tends to be quite small, i.e., < 10 cm H$_2$O (0.14 psi) for uniform sands (uniformity coefficient, $C_u \leq 2.5$) commonly used as filter pack. This will be so even in cases where the filter pack in a developed well is adequately preventing fines from the formation from entering the well. Therefore once there is sufficient applied pressure to displace all the water within the sparge well down to the top of the sparge screen, air readily enters the filter pack and displaces water from it. Buoyant forces are expected to cause the air to accumulate first at the top of the filter pack.

TABLE 2-1

Pressure/Pressure Head Conversions

1 bar	Units of Pressure $= 10^5$ N m^{-2} $= 0.987$ atmospheres $= 14.5$ psi $= 10^6$ dynes cm^{-2} $= 100$ kPa
and is equivalent to:	Units of Pressure Head 1020 cm column of water 75.01 cm column of Hg

d. Formation Air-Entry Pressure. The fourth component of the injection pressure is the air-entry pressure of the formation, P_e which is related using capillary theory to the pore size of the largest pores adjacent to the filter pack,

$$P_e = 2\sigma/r = 4\sigma/d \qquad\qquad [2\text{-}3]$$

where: P_e is the air-entry pressure (gm cm^{-1} sec^{-2}),
            σ is the surface tension (gm sec^{-2}) of water in air, and
            r is the radius and d the diameter (cm) of the constrictions along
            the largest pores of entry.

Assuming that pores are cylindrical and the solid-liquid contact angle is zero, Eq. [2-3] can be used to calculate the air-entry pressures of pores of various size (Table 2-2). Air-entry pressures of formations range from negligible for coarse-textured media such as coarse sands and gravels, to values of $\geq$ 1 m H_2O (1.4 psi) for medium-textured soils such as silts. Care needs to be exercised when using Eq. [2-3] and/or Table 2-2 to predict air-entry pressures in soils consisting of a variety of pore-sizes, because the largest pores may not necessarily be continuous throughout the soil matrix. The inflection point, P_{infl} of a Van Genuchten (1980) curve fitted to the soil moisture retention data (paragraph 3-3a(2)), which represents the predominant pore size within the soil (Baker et al. 1996), is therefore the recommended parameter to employ when estimating P_e. Under dynamic conditions, an initially-saturated soil undergoing air entry will first begin to be permeable to air at this inflection point P_{infl} (White et al. 1972; Baker et al. 1996). P_{infl} is thus the effective air entry pressure that should be used for design purposes (Baker and McKay 1997).

e. Air Entry Process. Where a range of pore sizes is present in the subsurface, which is almost always the case even in seemingly uniform sands, silts, or clays, initial air entry naturally takes place via the largest pores available. The largest pores are the paths of least resistance. If the largest network of pores is capable of conducting all the air that is injected into the well, then the pressure will not rise above the air-entry pressure, and smaller pores will remain liquid-filled. If, however, the combined conductivity of the largest pores is insufficient to convey away from the well all the air that is being injected, the applied pressure will rise, exceeding the air-entry pressures of the next smaller pore-size class. As the capillary pressure of the soil rises (as it must with higher air saturations and lower water saturations), the air permeability also increases. (Capillary pressure is defined in EM 1110-1-4001.) If the airflow being conveyed into the well can now be accommodated, the air-filled porosity will not increase further; otherwise, the process of displacement of water from smaller pores will continue until a dynamic equilibrium is attained between applied pressure and airflow (Baker et al. 1996).

TABLE 2-2

Representative Values of Air-Entry Pressure

Typical Soil Description	Diameter of Largest Pore (μm)	Air-Entry Pressure (psi)	Air-EntryPressure(kPa)
Coarse sand, macropores	>1000	<0.044	<0.3
Fine to med. sand	100	0.44	3.0
Silt	10	4.4	30
Silty clay	<1	>44	>300

f. Implications. Unless the resulting air-flow channels are small, close together, and well-distributed, mass-transfer external to them of (a) contaminants into the air-filled channels, and (b) oxygen in the reverse direction for aerobic biodegradation, will both be limited by aqueous-phase diffusion (Johnson 1994; Mohr 1995). Mohr (1995) proposed a conceptual model of the mass transfer across the air/water interface and the associated oxygen and hydrocarbon concentration profiles (Figure 2-4), and concluded that unless air-filled channels are small and well-distributed, diffusion-limited transfer will limit the effectiveness of IAS (Figure 2-5). The degree of soil homogeneity and isotropy are the most important determinants of air channel distribution during IAS. Soils such as interbedded sands and silts or other types of stratified deposits in which air permeability varies with direction and/or depth tend to sustain preferential airflow within the zones of higher permeability, which may or may not coincide with locations or layers having elevated contaminant concentrations. Uniform fine sandy or silty zones generally possess the most isotropic air permeabilities, and consequently are most appropriate for IAS as they are capable of producing a uniform and reasonably predictable ZOI. Conversely, soils such as massive clays having low values of air permeability are not amenable to IAS as excessively high air entry pressures can lead to soil fracturing and a low number of preferential flow channels conducting the entire air flow. An exception may be clays that are highly fractured. A recent API project completed in clay till produced significant mass removal with IAS. The till was highly fractured and as a result both NAPL and the IAS air flowed through the fractures (Johnson, R.L., Personal Communication, 1997). Research into the relationship between soil type, applied pressure, and airflow distribution is ongoing.

2-7. Groundwater Mixing.

a. Mixing Through Displacement.

(1) The introduction of air into a water-saturated formation displaces some of the water (Figure 2-6). The upward displacement of the water grows ("the expansion phase") while air makes its way to the water table surface, creating a transient groundwater mound (Boersma et al. 1993). Researchers using geophysical visualization tools (Acomb et al. 1995; Schima et al. 1996) have observed a tendency in uniform sands for some portions of the initially dewatered zone to resaturate while stable airflow patterns become established ("onset of collapse"). Meanwhile the mound dissipates radially outward (Figure 2-7) until a stable water table condition presents itself (Lundegard 1995). Upon depressurization of the sparging, such as when the compressor is turned off, many of the air-filled channels will resaturate as the formation reimbibes water, and the water table is seen to collapse temporarily. This condition too is transient and will not result in significant groundwater flow (Boersma et al. 1993; Lundegard 1994) (Figure 2-8). Turning the IAS system alternately on and off ("pulsing") is a method of increasing air/water contact and groundwater mixing. Each displacement of water represents more vertical (and horizontal) mixing than is normally seen in groundwater although the
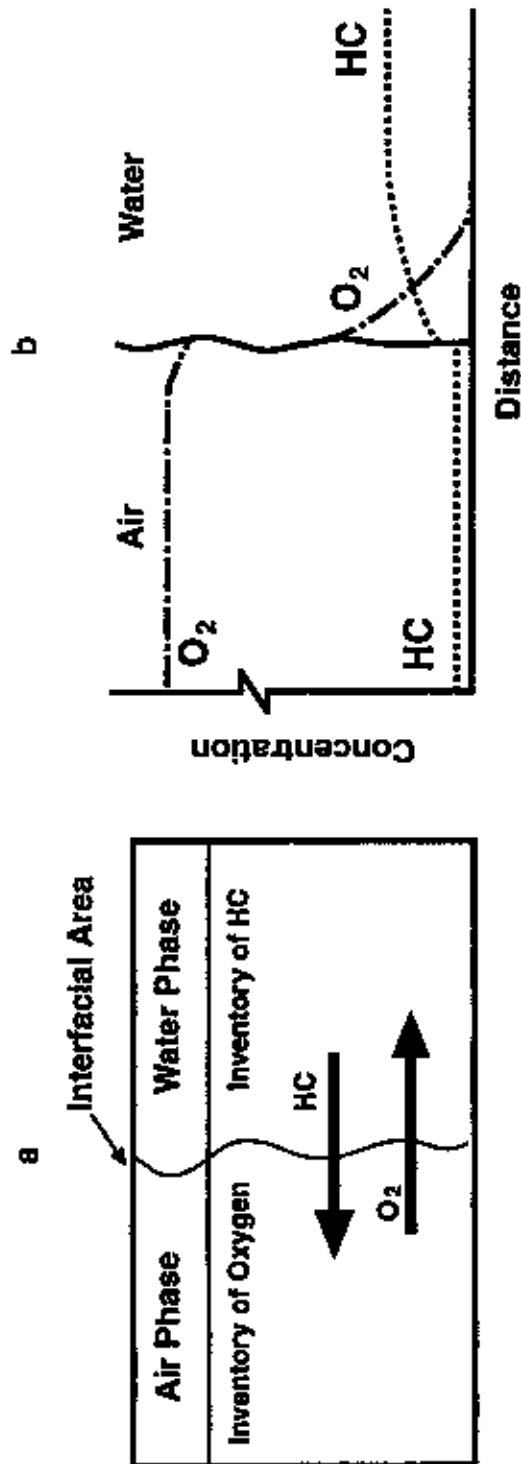
2-13

Figure 2-4. Mass transfer during IAS: (a) conceptual model, and (b) oxygen and hydrocarbon concentration profiles across the air/water interface (Mohr 1995)
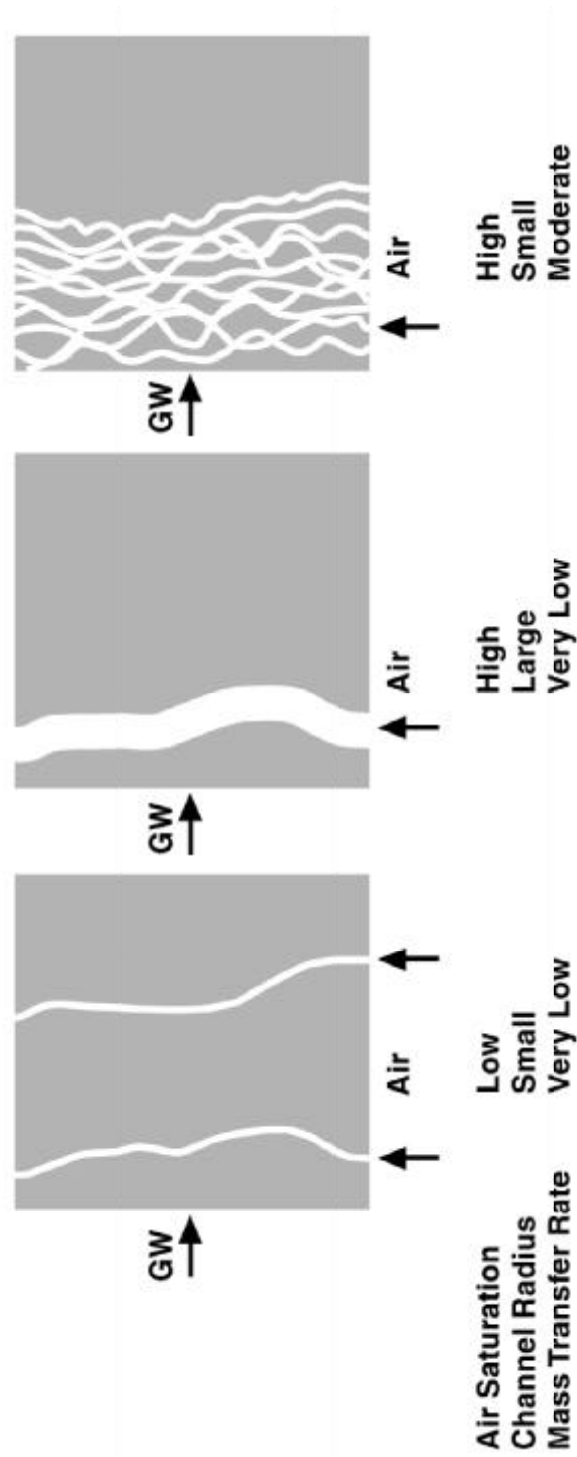
Figure 2-5. Effective air sparging requires high air saturation and finely dispersed air channels. GW indicates groundwater flow (Mohr 1995)
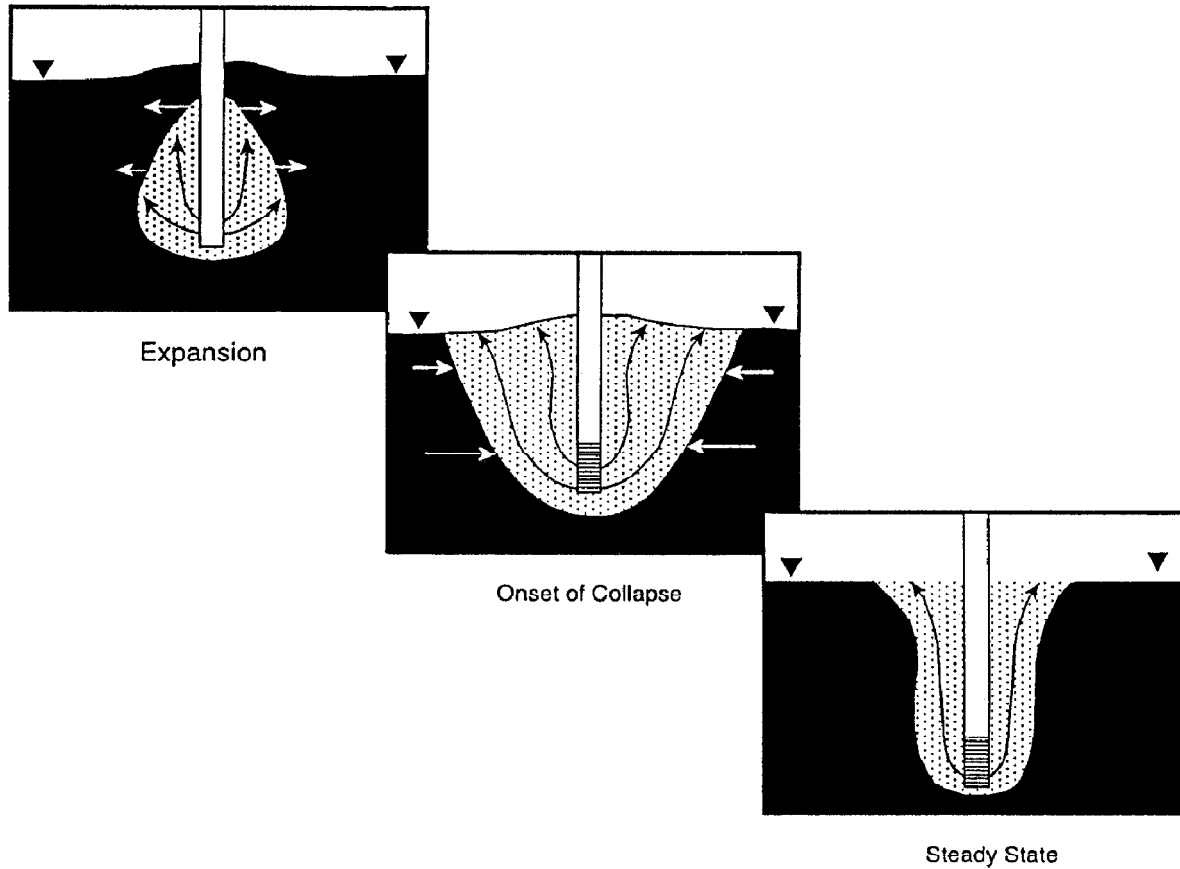
Expansion

Onset of Collapse

Steady State

Figure 2-6. Schematic representation of the behavioral stages occurring during continuous air sparging. Black arrows indicate air flow; white arrows indicate water flow. Mounding first develops during the transient expansion stage, dissipates during the collapse stage, and is generally negligible at steady state (Lundegard 1995).
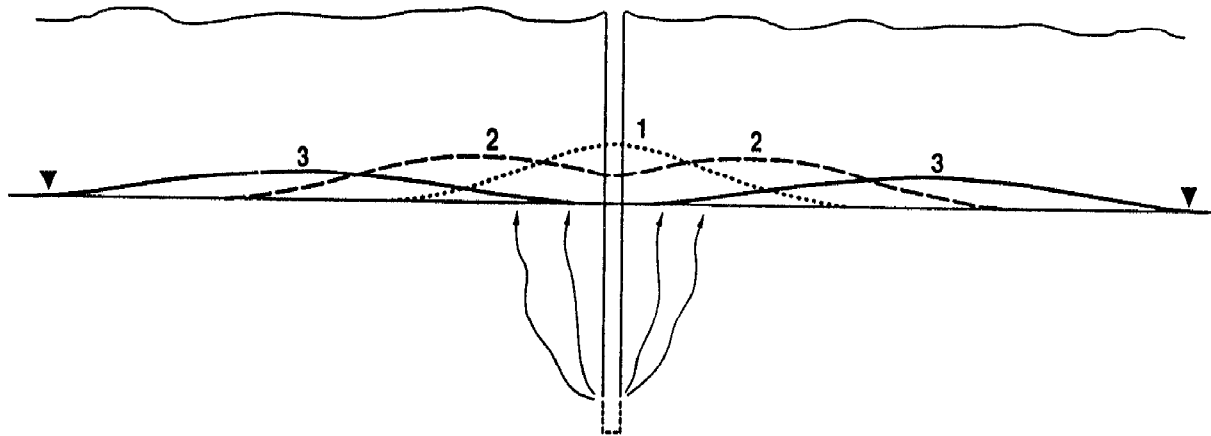
Figure 2-7. Schematic cross section representing progressive mounding behavior at three times: (1) expansion; (2) onset of collapse; (3) approach to steady state (Lundegard 1995)
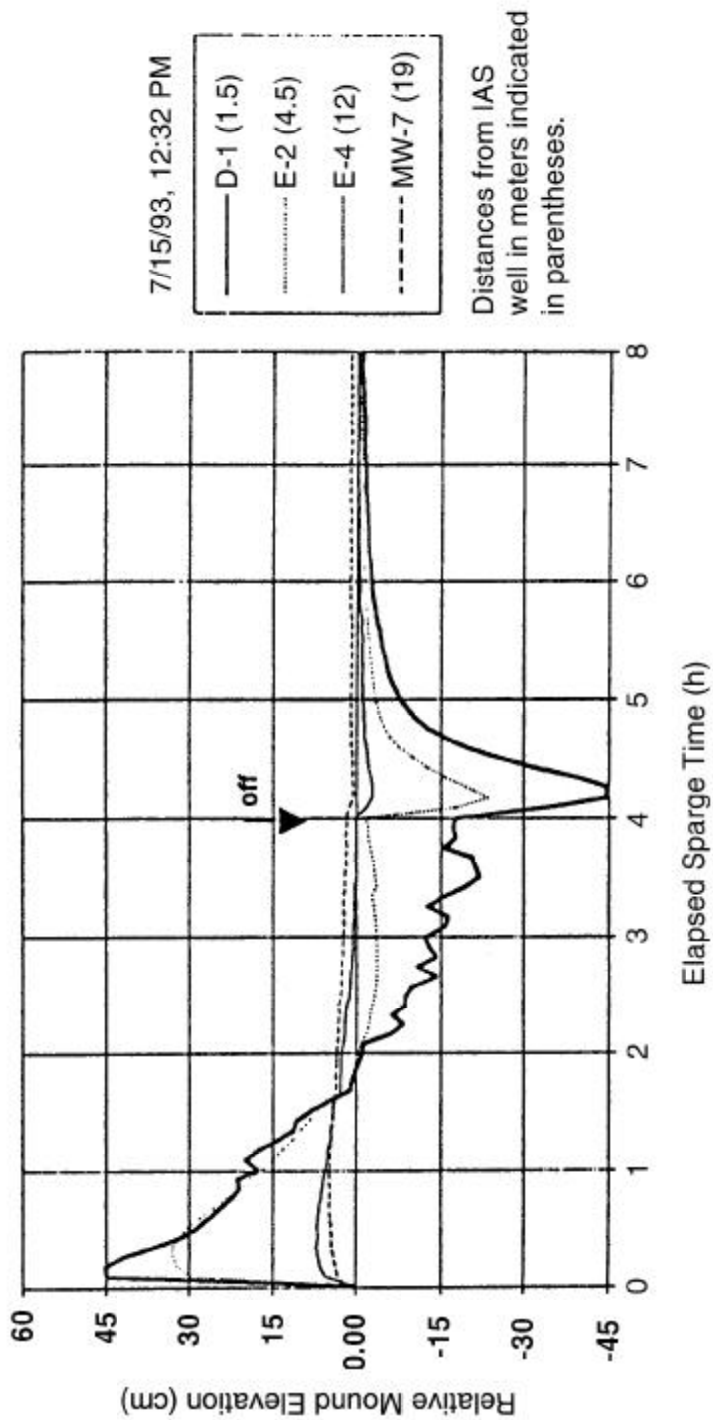
Figure 2-8. Changes in water table elevation vs time (ground water mounding) for four observation wells at various distances from the sparge well. (Lundegard 1994. Reprinted by permission of National Ground Water Association. Copyright 1994. All rights reserved.)

magnitude of the mixing effect appears to be relatively small (Johnson et al. 1996). This is a significant issue for cleanup because most subsurface processes are intrinsically mixing-limited, i.e., they are not fully mixed and thus are not well modeled as fully mixed reactors, to use chemical engineering terminology. The potential benefits of pulsing and associated mixing phenomena are described elsewhere (e.g., Johnson 1994; Clayton et al. 1995). It has been suggested that if the duration of the transient mounding period can be measured (i.e., by monitoring hydraulic head changes during IAS), this period may provide an estimate of the design duration and frequency of pulsing to deliberately maximize mixing of groundwater (Wisconsin DNR 1995). The degree to which mixing extends away from air-filled channels and thus helps overcome diffusion limitations is a matter of current research and debate (Johnson et al. 1996).

        (2) Pulsed injection can be conducted by cycling injection on a single-well IAS system or by altering flow in adjacent injection wells in a field. Pulsed injection is most effective for mobile dissolved phase contaminants due to the induced mixing. It is uncertain whether pulsed injection is effective for sorbed contaminants, or for residual (immobile) NAPL which, being immiscible with water, is not readily mixed. It has been observed that preferential flow channels tend to be re-established at the same locations during each pulse (Leeson et al. 1995). These re-appearing pathways may represent those that consolidate after each expansion phase. Information on pulsed operation is provided in paragraph 6-6b.

        b. Convection Currents. It has been suggested that convection currents may develop during IAS which could cause groundwater to circulate near the sparge well (Wehrle 1990). Such currents would form if the low density of the air stream causes the effective density of the fluid phase (air plus groundwater) near the well to be less than that of the groundwater at distances removed from the well, which would be anticipated only if air moves as discrete bubbles rather than in air-filled channels. Such currents would provide a mechanism for circulating water. These features may help move oxygenated water, but only if there is sufficient mass transfer from the vapor phase to oxygenate the groundwater. Convection currents are not viewed as a significant mechanism during IAS, however, because the effective density of water is not reduced except for the exceptional case of bubble flow (paragraph 2-5) (Wisconsin DNR 1993).

2-8. Associated Technical Issues. Aside from the issues described above which relate to conveying vapor through an aquifer, there are issues related to conveying the air to the injection points and from the vadose zone. At sites having very shallow water tables, the difficulties of capturing the vapors with SVE may result in fugitive releases of untreated VOCs. Care needs to be taken in handling the exhaust air to insure that such releases are minimized. Although the equipment used for IAS is almost entirely "off-the-shelf", the design must tie the individual items together into a system that moves the air in a controlled fashion. The control system requires careful

consideration to meet this need. Also, the operational design can influence
the need for operating permits, and these permits can affect the timing and
schedule for a project. The types of permits that may be required are
discussed in paragraph 8-2.

     a. Zone of Influence.

     (1) The area sufficiently affected by a sparge well or well field is a
primary design concern. Techniques applied to estimate the ZOI include
identifying the extent of measurable differences in pressure, dissolved gas
concentrations, and air-filled channels within the saturated zone. Gas
composition or pressure distribution in the unsaturated zone can also be
indicators of ZOI (paragraph 4-3b(7)). In this EM, ZOI is preferred over the
more widely used "radius of influence" (ROI) in recognition that the effects
of IAS tend to be non-uniform with respect to distance, depth and direction
relative to a sparge screen (Ahlfeld et al. 1994). A working definition of
the ZOI is the volume of the saturated zone over which air-filled channels are
relatively closely spaced, with air saturation >10% (Clayton 1996). The
effective ZOI radial distance is likely to be no more than 5 meters (or
approximately 15 feet). This saturated zone ZOI may be substantially smaller
than that indicated by changes in pressure or gas composition in the
unsaturated zone (paragraph 4-3b(7)) (Lundegard 1994). Other potentially
erroneous indications of ZOI also need to be discounted, such as evidence from
monitoring wells that are serving as a conduit for injected air and therefore
are subject to in-well aeration (paragraph 3-2b(2)), and evidence based on
mounding, that has been observed to extend far beyond locations of air
channels (paragraph 4-3c(8)). In some cases, although a few air pathways may
extend >30 m from the IAS well, they may not be within the zone where
treatment is needed (i.e., the air may spread under confining layers.)

     (2) Pulsed operation is designed so as to take advantage of the
recurrence of the expansion phase (Figure 2-6), during which the ZOI is
somewhat larger than during steady state IAS (McKay and Acomb 1996). Pulsing
and cycling are discussed further in paragraph 6-6b.

     (3) Consideration should be given to the fact that not all hydrocarbons
contained within the ZOI will be removed at the same rate. For example, at
increasing distances from the sparge well, air flow velocities within a given
channel must decrease due to frictional losses and accompanying pressure drop,
in accordance with Darcy's Law or models of pipe flow, depending upon the
scale. As a result, the rate of interphase mass transfer and hence
hydrocarbon recovery is reduced.

     b. Promotion of Biodegradation.

     (1) In addition to IAS stripping VOC from the groundwater, air sparging
also stimulates biodegradation of many volatile and semi-volatile
contaminants. Biodegradation will decrease or potentially eliminate the

amount of VOC which must be captured and/or treated at the surface. When enhanced biodegradation is the primary intent of the air sparging system, then this technique is termed biosparging.

(2) Dissolved oxygen is often the factor that limits biodegradation in the saturated zone. IAS is potentially a very cost-effective way to increase dissolved oxygen (DO) levels in the desired zone. However, since the solubility of oxygen from air is rather low at normal groundwater temperatures (ranging from 8 ppm at 25°C to 13 ppm at 5°C), the rate that oxygen can be dissolved into groundwater is often slower than the rate that microbes consume the oxygen. Thus it may be difficult to deliver adequate levels of oxygen to optimize biodegradation in contaminated regions.

(3) Despite this mass transfer limitation, IAS is generally the most cost-effective method available to introduce oxygen into the saturated zone. Other oxygen delivery mechanisms include injection of liquid hydrogen peroxide; sparging with pure oxygen; and slow release solid peroxide products such as Oxygen Release Compound (ORC). Per kilogram of oxygen delivered, IAS is typically orders of magnitude less expensive than other oxygen delivery methods.

(4) When considering biosparging, it is important to evaluate the relative masses of: 1) oxygen that can be sparged and dissolved into the groundwater, and 2) degradable hydrocarbons present in the saturated zone. Estimating the mass of contaminant below the smear zone (i.e., the mass of dissolved contaminant and the mass of sorbed contaminant), the mass of oxygen necessary for biodegradation can be calculated. Typically, approximately 3 grams of oxygen are necessary to biodegrade 1 gram of petroleum hydrocarbon. Methods for estimating the rate of oxygen dissolution during biosparging are presented by Johnson (1994) and Mohr (1995). A comparison of the mass of oxygen necessary for biodegradation and an estimate of the rate of oxygen dissolution into groundwater during biosparging should be included as part of the evaluation of biosparging. This mass comparison can also be used to check design parameters of a biosparging system (such as the number of sparge points and the anticipated period of system operation) as developed according to the guidance provided in Chapter 5.

(5) A possible negative effect of the growth of aerobic microorganisms is the potential for biofouling of IAS well screens and/or filter pack materials near the sparge well. Although this does not generally appear to be a major problem, it is discussed further in paragraph 6-4a.

(6) At some sites, anaerobic dechlorination of chlorinated ethenes (e.g., TCE) that occurs naturally in groundwater produces vinyl chloride (VC). IAS can inhibit the production of VC by maintaining aerobic conditions and can also strip the VC from the groundwater. Anaerobic dechlorination of chlorinated ethenes and the conditions that affect this process is discussed

at length in the U.S. Air Force's protocol on natural attenuation of chlorinated solvents, described by Klecka et al. (1996).

2-9. Technology Assessment: Effectiveness and Limitations.

a. Advantages of IAS. The primary advantages of IAS over alternate remedial technologies include relative simplicity and low cost. IAS equipment is readily available and easy to install with minimal disturbance to site operations.

(1) IAS components can be installed during site investigations by completing borings as sparge wells, SVE wells and/or monitoring points. Additional subsurface components can be installed cost-effectively via direct push methods, where the soil geology and required installation depth will permit their use.

(2) For certain contaminants, IAS can remediate through both aeration and biodegradation.

(3) IAS is compatible with other remedial methods such as those employed to treat vadose zone contamination (e.g., SVE, and bioventing (BV)).

(4) IAS can be employed to effectively limit off-site migration of dissolved contaminants.

(5) Once implemented, IAS systems require minimal operational oversight relative to SVE systems.

(6) For IAS systems not matched with SVE, waste streams are not generated, and therefore do not need to be treated.

(7) The technology is judged by many practitioners as being a potentially effective method available for treating smear zone contamination.

b. Disadvantages of IAS. Disadvantages to IAS over alternate remedial technologies are primarily related to site physical and/or chemical characteristics which either preclude contaminant removal or alter contaminant mobility to threaten potential receptors.

(1) Contaminants are not effectively removed by IAS when, due to low Henry's Law constants or low volatilities, they are not amenable to air stripping.

(2) Semi-volatile contaminants with low aerobic biodegradability are not effectively treated.

(3) Geologic conditions such as stratification, heterogeneity, and anisotropy will prevent uniform air flow and cause IAS to be ineffective. The

deeper below the water table that IAS wells are installed, the more likely will stratification be encountered that will divert the airflow laterally.

    (4) Free product (NAPL) at greater than residual saturations constitutes a virtually inexhaustible source of VOCs that may come only into limited contact with air. This is especially likely to be a concern relative to DNAPLs; some LNAPL sites have reportedly responded well to IAS.

    (5) When a sparge curtain is used in an effort to contain a dissolved phase plume (paragraph 2-2c), the resulting zone of reduced hydraulic conductivity, can, if not managed, permit the plume to bypass the IAS treatment zone.

    (6) Potential exists for IAS to induce migration of contaminants, and to generate fugitive emissions.

    (7) Additionally, IAS has a limited areal coverage, and consequently a significant number of injection wells are commonly required.

2-10. Technology Status. IAS has been implemented over the past several years at thousands of locations to address a variety of contaminants. However, IAS cannot currently be considered a mature remediation technology. Current research into IAS has primarily focused on defining air and groundwater physical dynamics. Contaminant fate and transport has been less well researched, and questions remain about treatment duration and site closure, particularly at locations where regulatory targets require that sorbed contaminants must be removed.

2-11. Conditions Amenable to IAS. Primary considerations for sites amenable to IAS include the site geology and contaminant type and phase. Table 2-3 provides a general summary of these considerations. Secondary considerations include adjacent receptors, whether currently threatened or potentially threatened after installing IAS, and infrastructure concerns, such as power availability, access, and proximity of active installations. It should be noted that Henry's Law constants for various contaminants are specified for steady state conditions between phases. These may be optimistic indicators for actual IAS systems, in which dissolved concentrations in groundwater adjacent to air channels are not in equilibrium with groundwater concentrations distant from air channels. Figure 2-9, IAS Implementation Decision Tree, displays a generalized description of the process of evaluating and implementing IAS.

2-12. Success Criteria. In a broad sense, IAS is successful if its application to a site results in regulatory "closure," i.e., no further remediation work is required by the appropriate agency. Specifically, success consists of:

TABLE 2-3

Conditions Amenable to IAS

Parameter	-	O	+
Contaminant Type	Weathered Fuels Lubricating Oils Hydraulic Fluids Dielectric Fluids PCBs	Diesel Fuel Jet Fuel Acetone	MOGAS AVGAS Halogenated Solvents[1] Benzene Toluene
Geology	Silt and clay (interbedded) Massive clay Highly organic soils Fractured bedrock Stratified soil Confining layers	Weakly stratified soils Sandy silt Gravelly silt Highly fractured clay	Uniform coarse- grained soils (gravels, sands) Uniform silts
Contaminant Phase	Free Product	Sorbed	Dissolved
Contaminant Location	Within confined aquifer; near bottom of unconfined aquifer	Within shallow aquifer	Near water table
Contaminant Extent	Large plumes[2]	Modest-size plumes	Small plumes
Hydraulic Conductivity (cm/s)	$<10^{-5}$	10^{-5} to 10^{-4}	$>10^{-4}$
Anisotropy	High degree of anisotropy	Moderate degree of anisotropy	Isotropic

- IAS likely to have limited effectiveness
o IAS likely to provide some benefit
+ Well suited for IAS
[1] IAS is generally applicable to halogenated ethenes, ethanes, and methanes.
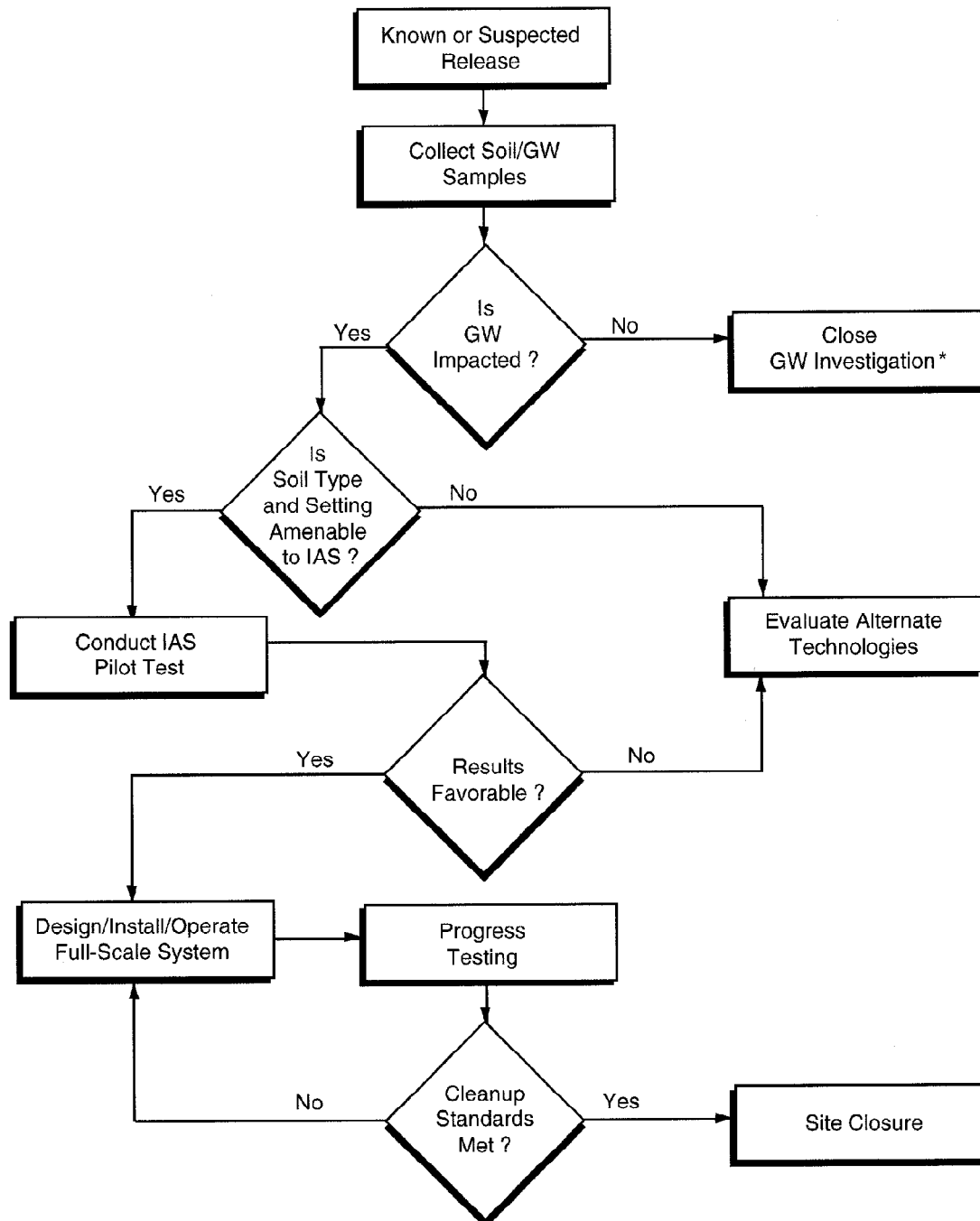**[2] Sparge curtains may be effective in management of migration within large plumes (paragraph 2-2*c*).**

Figure 2-9. IAS implementation decision tree.
* A leaching assessment for evaluation of groundwater impact may be performed at this point.

a. effective delivery of air or other gases into the desired zone;

b. distribution of the introduced gas through the saturated subsurface at the design ZOI;

c. achievement of the design loading of the vapor with VOC, and/or of the design biodegradation rate in the groundwater (which will vary depending upon concentration and dominant phase of remaining contaminant);

d. effective capture and treatment of the sparged vapor in the vadose zone near the water table;

e. attainment of the design hydrocarbon removal rates from the subsurface; and

f. removal of contamination to below regulatory levels.

Achievement of a negotiated, risk-based closure following IAS can also be considered a successful outcome even if cleanup standards have not been met (paragraph 7-2). Other success criteria include achievement of the project objectives within the allotted schedule and budget.

2-13. <u>IAS Models</u>.

a. Although there are an increasing amount of operational data available to evaluate the effectiveness of IAS systems, mathematical models may be useful in the design process. Information (i.e., site data acquired from laboratory and field-scale pilot tests) would be used as input parameters in a given analytical or numerical model. Several attempts have been made to generate mathematical and computer models which describe the processes associated with IAS. Most met with little success because little was known about the actual rate of mass transfer that was occurring during air sparging, and it was impossible to validate model results when compared to field data.

b. Prior to model development, a conceptual model must first be proposed. Early modelers assumed the injected air moved as isolated, random bubbles. With the recognition that injected air actually moves through discrete, continuous, air-filled channels separated by regions of complete water saturation, IAS models incorporating multiphase flow have been developed.

c. A number of investigators have advanced the principles associated with these conceptual models and have developed mathematical models to assist in the design of air sparging systems. Several noteworthy IAS models have been developed and are presented in the literature. Five are cited below:

(1) Norris and Wilson (1996) present the results of a sparging and biosparging model based on air channeling, and air channeling and VOC/O_2 transport driven by dispersion, respectively.

(2) Mohr (1995) presents an analytical solution for estimating the rate of biodegradation associated with air sparging.

(3) Rutherford et al. (1996) present the results of a one-dimensional finite difference model based on the equations for a cross-flow bubble column, which was used to calculate a lumped value of liquid mass transfer coefficient and interfacial surface area.

(4) The Seattle District, USACE has used a numerical model called POREFLOW® to simulate air sparging. A public domain version of the model, POREFLO-3© is available (Runchal and Sagar 1989); however, the distributor has upgraded a proprietary version of the model (ACRI 1996). POREFLOW® runs on most any platform; the PC code is less than 1Mb in size, but requires at least 10 Mb to operate the pre- and post-processor. POREFLOW® is a three-dimensional finite difference model which accounts for losses due to decay, solute transport and partitioning. It is capable of simulating compressible fluids (e.g., air) and heat transport. Input parameters include the following:

(a) porous media properties (e.g., hydraulic conductivity, permeability versus saturation relationships, pressure-saturation relationships, storage values, and density)

(b) fluid properties (mass, density, viscosity as a function of pressure and mole weight of gases)

(5) TETRAD (DYAD 88 Software, Inc.) is a finite difference simulator, originally developed for the study of multiphase fluid flow and heat flow problems associated with petroleum and geothermal resource evaluation (Lundegard and Andersen 1996). Lundegard and Andersen (1996) modified the code for IAS applications to account for a air-soil, constant pressure, surface boundary condition. TETRAD is capable of simulating three-dimensional, multiphase flow in complex, heterogeneous, anistropic systems. Vinsome and Shook (1993) describe the structure and solution methods for TETRAD.

d. A limitation associated with IAS models is that the heterogeneities that control airflow paths are on a scale much finer than the available site characterization data. The processes that IAS models must incorporate include multiphase flow, buoyancy and capillary forces acting on air, and soil variability on a small and large scale (perhaps by stochastic methods).